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FOREWORD

The Environmental Protection Agency was established to coordinate administration of the major Federal programs designed to protect the quality of our environment.

An important part of the agency's effort involves the search for information about environmental problems, management techniques and new technologies through which optimum use of the nation's land and water resources can be assured and the threat pollution poses to the welfare of the American people can be minimized.

EPA's Office of Research and Development conducts this search through a nationwide network of research facilities.

As one of these facilities, the Robert S. Kerr Environmental Research Laboratory is responsible for the management of programs to: (a) investigate the nature, transport, fate and management of pollutants in groundwater; (b) develop and demonstrate methods for treating wastewaters with soil and other natural systems; (c) develop and demonstrate pollution control technologies for irrigation return flows; (d) develop and demonstrate pollution control technologies for animal production wastes; (e) develop and demonstrate technologies to prevent, control or abate pollution from the petroleum refining and petrochemical industries; and (f) develop and demonstrate technologies to manage pollution resulting from combinations of industrial wastewaters or industrial/municipal wastewaters.

This report contributes to the knowledge essential if the EPA is to meet the requirements of environmental laws that it establish and enforce pollution control standards which are reasonable, cost effective and provide adequate protection for the American public.

William C. Galegar
Director
Robert S. Kerr Environmental Research Laboratory

ABSTRACT

An electronic circuit has been developed which acts as an electronic ice bath for chromel-constantan thermocouples. The electronic ice bath is accurate to within ± 0.2°C from -25°C to +50°C. Simultaneously, the thermocouple output is scaled and linearized such that the temperature can be read directly in °C with a sensitivity of 100 mV/°C with 0 VDC at 0°C. Circuit diagrams and construction considerations are included to allow the reader to construct a functioning unit.

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SECTION 1

INTRODUCTION

Remote temperature measurement is a necessary part of many research investigations. Air and soil temperatures are commonly recorded to help understand the transport phenomena in heat and water flow. Several different types of transducers or detectors are in common use for this purpose. The most commonly used are thermocouples and thermistors. The major drawback with thermocouples is a lack of sensitivity and the requirement for a reference junction. On the other hand, thermistors have a high output versus temperature but lack adequate interchangeability.

At the Robert S. Kerr Environmental Research Laboratory field station in Ada, Oklahoma, studies are being conducted to evaluate wastewater treatment by land application. As a necessary part of this research effort, temperature measurements are required in the assessment of physical, chemical, and biological processes. To adequately monitor the environmental processes, an instrument capable of monitoring multiple input thermal transducers with an accuracy of ± 1°C from 25°C to +40°C was required. Commercial units with adequate capabilities were not readily available. For this reason, an instrument was developed to meet the specific needs of the experimental studies.

This report deals with an electronic method of providing an accurate reference junction for a chromel-constantan thermocouple, signal conditioning to linearize the output of a thermocouple pair, and signal gain such that output is 100 mV/°C.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

A temperature readout instrument can be constructed such that output from the instrument is 100 mV/°C using a chromel-constantan thermocouple for a detector. The accuracy of the instrument is ± 1° C over a range of -25 to 40° C for the detector when the instrument operating temperature ranges from -25°C to +75°C. An auxiliary output is available which assesses the temperature of the instrument and is accurate ± 0.2°C from -25°C to +50°C with an output sensitivity of -100 mV/°C.

The instrument should be particularly useful for temperature measurements in remote locations where a supply of ice is not readily available for use as a reference temperature. The approach should be adaptable to other thermocouple materials by changing values of R_1 and R_2 in Figure 1. The two resistors are used to give a calibrated output for the instrument. The range of temperature could be expanded; however, the accuracy of the measurement will be reduced because the actual output of the thermocouple was assumed to follow the binominal equation $T = a + bV + cV^2$. The approximation is adequate over a temperature range of 100 Celsius degrees.

SECTION 3

DESIGN AND THEORY OF OPERATION

The theory of operation of the thermocouple has been described in numerous textbooks and is extensively discussed in a monograph by Dike (1). The actual design of the included circuitry is based on the 1971 National Bureau of Standards reference tables for thermocouples as reproduced in Omega Engineering's Temperature Measurement Handbook (2). These data were fitted by the method of least squares to the equation

$$T = a + b\,(V) + c\,(V)^2 \qquad (1)$$

where T = temperature (°C)

V = thermoelectric voltage in absolute millivolts

a, b, and c are constants

The values obtained are 0.00113, 17.025, -0.2033 for a, b, and c, respectively. Table 1 gives a range of values which might normally be expected for environmental measurements and the predicted temperature based on Equation 1. Column 1 of Table 1 is an assumed temperature. By determining thermoelectric voltage (V), the theoretical network response (T) is calculated and presented as Column 2. The error is then the difference in the two temperatures.

The actual circuit, Figure 1, is then based on Equation 1 and consists of four sections:

1) Preamplifier which boosts the thermoelectric voltage 1,000 times, so that the magnitude of the voltage is in the range that can be easily manipulated.

2) Squaring unit which is an analog functional block.

3) Summing unit which sums all values.

4) Reference unit which measures the absolute temperature of the reference junction and provides an output voltage linearily proportional to the absolute temperature of the reference junction.

The preamplifier, A_1 in Figure 1, is an instrumentation amplifier with a gain of 1,000. The instrumentation amplifier differs fundamentally from an operational amplifier. It is designed to be used as a closed-loop differential amplifier. The necessary feedback networks are contained within the amplifier. Ideally, the instrumentation amplifier responds only to the difference between the two input signals and exhibits an extremely high input impedance between the two terminals and each terminal to the ground. The output voltage is developed single-ended with respect to ground and is equal to the product of the amplifier gain and the difference of the two input voltages:

$$E_0 = K (E_2 - E_1) \qquad (2)$$

where E_0 = output voltage

E_1 = input voltage 1

E_2 = input voltage 2

K = gain of the amplifier

with the instrumentation amplifier used, $K = 100K\Omega/R_0$.

Thus, $V_{TP1} = 1,000 (E_{ref} - E_{sens})$.

where V_{TP1} = voltage at Test Point 1

E_{ref} = thermoelectric voltage of reference junction

E_{sens} = thermoelectric voltage at measuring junction

The multiplier's output is given by Equation 3

$$E_0 = (X_1 - X_2)\ (Y_1 - Y_2)/10 \tag{3}$$

with the input as described in Figure 2. As applied, the output observed at $TP_2 = -(V_{TP1})^2/10$.

The reference junction temperature is measured using a semiconductor. The thermal effect on the foreword current of a P-N junction is expressed by Equation 4 as presented by Shea (3).

$$I = I_0 \{\exp[(g/mKT)\ (V-IR_s)]-1\} \tag{4}$$

where I = foreword current

I_o = reverse saturation current of the diode

g = electron charge = 4.8×10^{-10}

K = Boltzmann's constant = 1.37×10^{-16}

m = constant representing the effects of diffusion current flow

R_s = equivalent series internal resistance of diode

T = absolute temperature of diode junction

V = foreword voltage

Widlar (4) showed further, that by holding the current constant, the expression for the foreword voltage drop across a diode could be written as

$$V_f = [1-(T/T)]\ V_{go} = (V_{fo}T/T_o) = (KT/g)/n\ (T_o/T) + (n-1)\ (1+T/T_o)\ KT/g \tag{5}$$

where V_f = foreword voltage drop across the diode

V_{fo} = foreword voltage drop at T_o

V_{go} = the extrapolated energy gap for the semiconductor material at absolute zero

n = constant

T = absolute temperature

T_o = absolute temperature at which V_{fo} is measured

Enfield and Tromble (5) measured the thermal characteristics of several IN4154 diodes and determined that the mean foreword voltage drop at 0°C with 1 ma foreword current was 618 mV with a standard deviation of 15 mV. The mean thermal sensitivity was determined to be 1.9 mV/°C with a standard deviation of 0.12 mV/°C. Based on these experimental measurements a diode thermometer was designed which measures the temperature of the reference junction and yields an output voltage at TP_3 of -100 mV/°C with 0 mV at 0°C.

Resistor R_6 functions with reference zener diode DZ1 to generate a reference voltage for the circuit.

R_7 and R_8 form a voltage divider which maintains the base of transistor Q_2 at a reference voltage (VR).

Transistor Q_1 is in thermal contact with transistor Q_2. Thus, the thermal error caused by the change in the foreword voltage drop of Q_2, in current flowing through R_9, is compensated by an equal change in VR. This is optimized in the circuit by causing the same current to flow through Q_1 and Q_2. Thus, the current which flows through diode (D_1), the thermal detector, equals (VR-V_{be} of Q_2)/R_9 or approximately 1 ma. Amplifier A_3 acts as a single-ended summing scaling buffer. Analyzing the circuit in its two parts, first analyze Figure 3, which is one configuration for a scaling buffer.

The gain of the circuit converts the thermal sensitivity of the diode, approximately 1.9 mV/°C, to -100 mV/°C or a gain of approximately 53. With the components

in Figure 1 the gain is adjustable from 40.2 to 54.1.

The output of the reference thermometer is zeroed at 0°C by summing a current from the zener reference voltage into the inverting input of A_3. The inverting input acts as a virtual ground at V_{diode} @ 0°C. Thus, to zero the output

$$\{[0-(V_{diode})]/R_{11}\} + \{[V_{zener} - (V_{diode})]/R_T\} = 0$$

Assuming $V_{diode} = -618$ mV and $V_{zener} = 6$ V, then

$$618/R_{11} + (6000 - 618)/R_T = 0 \quad \text{or} \quad R_T = 8.7\, R_{11}$$

With the values in the circuit, the range of R_T is 7.5 to 9.7 times R_{11} which allows for sufficient variation in diodes.

The final stage of the instrument is merely a summing amplifier that combines all the components and yields an output directly proportional to temperature with zero at 0°C. To obtain an output sensitivity of 100 mV/°C, the following resistance ratios must be maintained.

$$R_5/R_1 = 1.703$$

$$R_5/R_2 = 0.02033$$

$$R_5/R_{15} = 1$$

SECTION 4

CALIBRATION

There are three adjustments to be made prior to use of the instrument. The following calibration procedure should be satisfactory:

1) Place the reference diode (D_1) in an ice bath (0°C). The diode should be encapsulated to waterproof the junction.

2) Adjust RT_2 for 0.000 VDC ± 2 mVDC at TP_3.

3) Monitor TP_3 for sufficient time to guarantee thermal equilibrium between the ice bath and the reference diode.

4) Place the reference diode (D_1) in a water bath or suitable reference temperature device at approximately 100°C. Adjust RT_3 for an output sensitivity observed at TP_3 of -100 mV/°C. This adjustment should be made as accurate as the temperature is known.

5) Repeat steps 1 through 4 until no further adjustment is required. One calibration cycle is usually sufficient.

6) With the thermocouple reference junction at the same temperature as the thermocouple sensing junction, adjust RT_1 for 0.000 VDC ± 1 mVDC at TP_1.

After the above calibration procedure has been followed, the instrument can be placed in service.

SECTION 5

CONSTRUCTION CONSIDERATIONS

Since the instrument described is for measuring temperatures, errors caused by thermal drift of the components can be significant. Analysis of thermal drift errors is beyond the scope of this report. For a sensitivity analysis, the reader is referred to Tobey et al. (6) and Enfield and Hsieh (7) for a discussion of the problems. In the circuit described, precision resistors with thermal coefficient of 50 ppm/^{o}C were used throughout the construction. Transistors Q_1 and Q_2 were in thermal contact with each other as indicated by the dashed line around the two transistors. D_1 was bonded to the thermocouple reference junction indicated by the dashed square boxes in Figure 1, so as to maintain the references and D_1 at the same temperature.

TABLE 1. COMPARISON BETWEEN ACTUAL TEMPERATURE AND PREDICTED NETWORK TEMPERATURE

ACTUAL	THEORETICAL NETWORK RESPONSE	ERROR
-25	-24.6	0.4
-20	-19.8	0.2
-15	-15.0	<0.1
-10	-10.0	<0.1
- 5	- 5.2	0.2
0	- .2	0.2
5	4.8	0.2
10	9.9	0.1
15	15.0	<0.1
20	20.1	0.1
25	25.3	0.3
30	30.5	0.5
35	35.7	0.7
40	41	1.0
45	46.3	1.3
50	51.7	1.7

Temperature = °C

TABLE 2. PARTS LIST

RESISTORS*	(In ohms unless specified)
R_0	100
R_1	See manuscript (5.87)
R_2	See manuscript (492 K)
R_3	50K
R_4	50K
R_5	10K
R_6	820
R_7	3.01K
R_8	3.01K
R_9	3.01K
R_{10}	2.74K
R_{11}	1K
R_{12}	7.5K
R_{13}	40.2K
R_{14}	16.2K
R_{15}	10K
R_{16}	47K 5%
VARIABLE RESISTORS (20 Turn Trimmer)	
RT_1	100K
RT_2	10K
RT_3	100K
CAPACITORS	
C_1	0.01 µf
SEMICONDUCTORS	
D_1	IN4154
DZ_1	IN821
Q_1, Q_2	2N3904
INTEGRATED CIRCUITS**	
A_1	3660K
A_2, A_3	3501A
MULTIPLIER	4205J

* All resistors 1% unless specified.
** Burr-Brown part numbers are listed for information only.

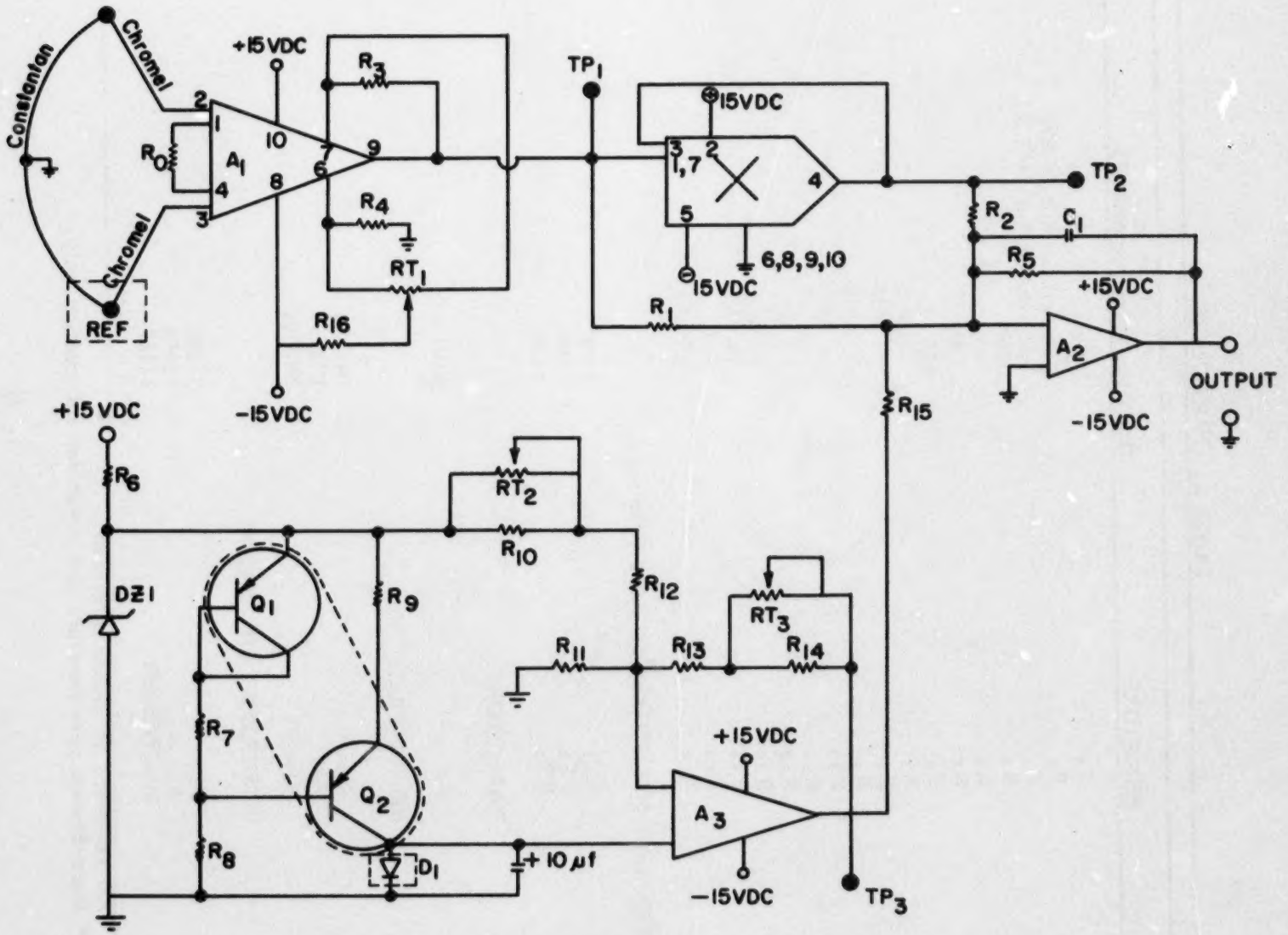

FIGURE 1 - SCHEMATIC DIAGRAM OF TEMPERATURE COMPENSATION NETWORK

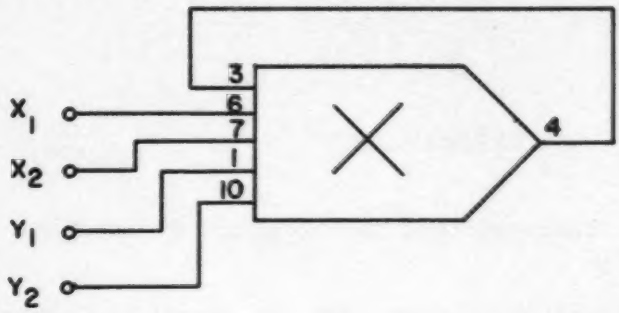

FIGURE 2 - PIN CONNECTION FOR BURR-BROWN MODEL 4205 MULTIPLIER

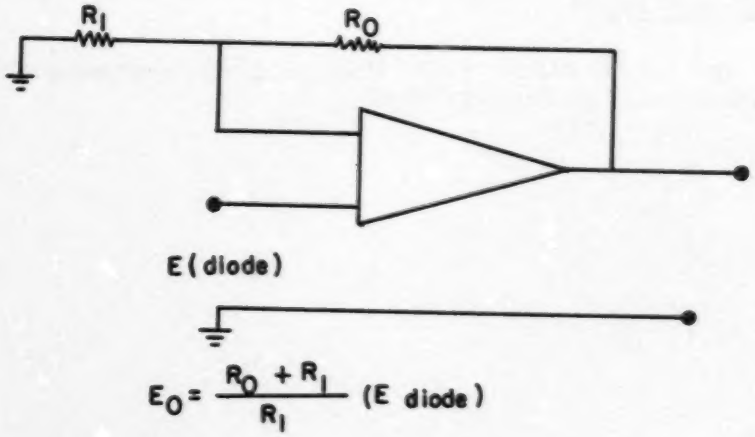

FIGURE 3 - SCALING BUFFER AMPLIFIER

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